Reinventing The Wheel -
VTOL Aircraft Taxonomy and Lexicon

Al Lawless, Aurora Flight Sciences, lawless.alan@auora.aero
Dan Newman, Boeing Advanced Vertical Lift, daniel.i.newman@boeing.com

1. ABSTRACT

New technologies enable and inspire a revolution in conceptualizing novel VTOL aircraft configurations. Investments in distributed propulsion, electric machines, advanced sensors and computational power is paying off. Regulatory review and approval, though, is hampered because the current categories and terms direct many designs to be handled as exceptions. This paper proposes lexicon and a comprehensive physics-based taxonomy that systematically captures all real and notional VTOL aircraft configurations, and language for describing propulsor types, with specific aircraft examples. The approach offered could streamline and simplify regulatory review of these novel VTOL aircraft.

2. INTRODUCTION

This paper addresses a taxonomy for aircraft with vertical takeoff and landing (VTOL) capability. While such aircraft have operated for nearly a century, recent technologies enabled more novel configuration possibilities than before. Many new configurations are not addressed by the existing categorization, so are fated to being outliers. Prior frameworks left us wanting, making regulatory review and approval challenging. All this has consequences for the workload and timeline for regulatory review. We therefore need a comprehensive framework and common language to methodically describe all of these possibilities and place them in context with familiar aircraft. Toward this goal, this paper proposes a taxonomy and expanded lexicon, provides examples of aircraft that populate this taxonomy, and offers compact illustrations showing the taxonomy structure.

This taxonomy and terminology expansion is needed primarily because the existing definitions, although well-suited for legacy VTOL aircraft, come up short when attempting to apply them to more novel aircraft. In essence, the existing definitions are no longer sufficiently comprehensive or descriptive. Furthermore, new classifications proposed have weaknesses that further complicate the situation. Of particular concern was a 2022 EASA proposal to change the helicopter definition, to limit them to two rotors - a feature we consider not actually relevant. More recently, the FAA embarked on an effort to address rules for powered lift aircraft. While well-intentioned, the powered lift definition effectively excludes certain VTOL configurations that are nearly identical to those included. Industry, academia, operators and regulators must expand our terminology and common understanding to keep pace with new possibilities.

Another motivation for developing and adopting a revised taxonomy and language is that, if properly organized, it allows characterizing common features that should in turn have common design and evaluation criteria. Organizations that write or negotiate acceptance standards are not adequately staffed to manage exceptions. A well thought-out taxonomy with clear organization and language describing aircraft can more efficiently and fairly package requirements. Ideally, established packages will help set the bar clearly and appropriately high and level the playing field for all. This ideal compares to the alternate where each manufacturer and overwhelmed regulators must start from scratch and re-negotiate methods and means for showing compliance to rules. Note that standards packaging does not remove flexibility. For civil certification purpose in the US, Title 14 CFR 21.17(b) allows applicants to negotiate custom airworthiness for special class aircraft that don't fit in an existing class. While retaining an ability to innovate and negotiate, applicants can at least plan ahead if key features connect to standards.

Established Definitions

Before expanding a taxonomy and terminology, it is important to recognize and respect established law. This topic requires reviewing categories, classes, and just a few definitions. At this time, there are seven aircraft categories that roughly outline intended use: transport, normal, utility, acrobatic, limited, restricted, and provisional. Often independent of an aircraft's use category is its class, which presently includes rotorcraft, glider, balloon, landplane, and seaplane.

Independent of but often conflated with aircraft category and class are those for pilot privileges (licenses). Here, the eight categories are: airplane, rotorcraft, glider, LTA, powered-lift, powered-parachute, weight-shift, UAS. Coincidentally, there are also eight pilot rating classes: single engine, multiengine, sea, land, helicopter, gyroplane, airship, balloon. Piloting some aircraft requires multiple class ratings (e.g., multi engine and helicopter) while others do not. Figure 1 presents the categories, classes, pilot privileges and pilot rating classes, with the authors' view of the alignment between them.

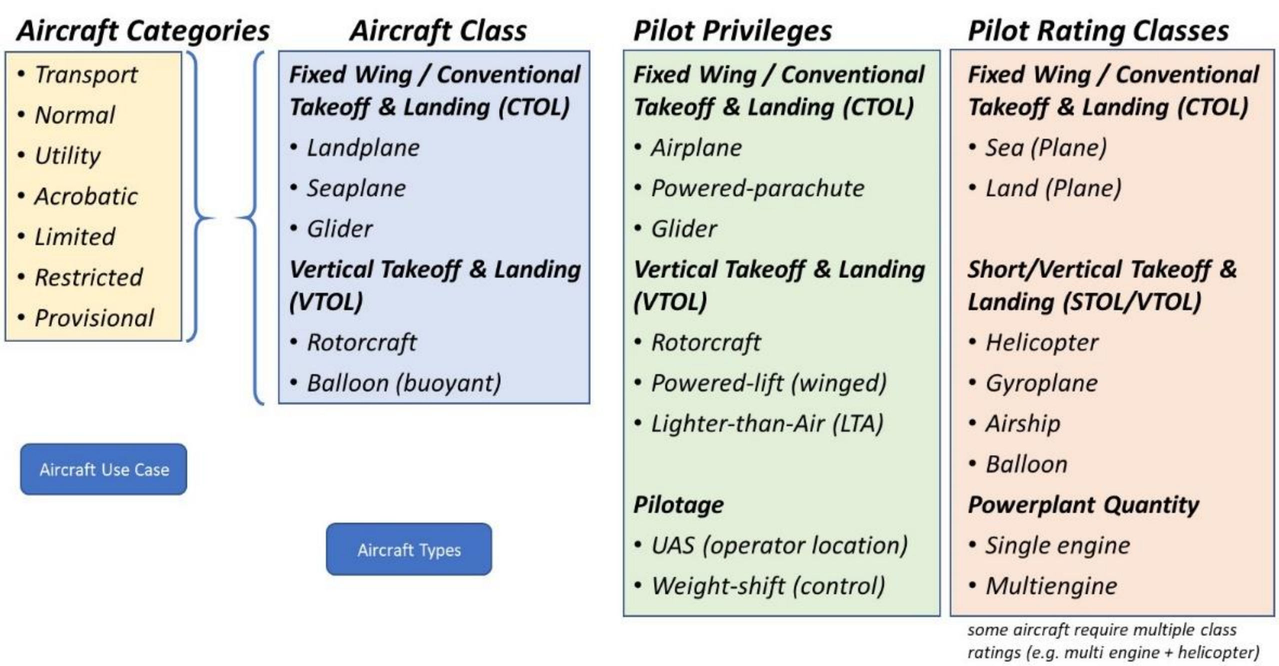

Figure 1 – Aircraft and Pilot Categories and Classes

For convenient reference, following are definitions in Title 14 CFR, Chapter I, Subchapter A, Part 1

Airframe *means the fuselage, booms, nacelles, cowlings, fairings, airfoil surfaces (including rotors but excluding propellers and rotating airfoils of engines), and landing gear of an aircraft and their accessories and controls.*

Rotorcraft *means a heavier-than-air aircraft that depends principally for its support in flight on the lift generated by one or more rotors.*

Gyrodyne *means a rotorcraft whose rotors are normally engine-driven for takeoff, hovering, and landing, and for forward flight through part of its speed range, and whose means of propulsion, consisting usually of conventional propellers, is independent of the rotor system.*

Gyroplane *means a rotorcraft whose rotors are not engine-driven, except for initial starting, but are made to rotate by action of the air when the rotorcraft is moving; and whose means of propulsion, consisting usually of conventional propellers, is independent of the rotor system.*

Helicopter *means a rotorcraft that, for its horizontal motion, depends principally on its engine-driven rotors.*

Powered-lift *means a heavier-than-air aircraft capable of vertical takeoff, vertical landing, and low speed flight that depends principally on engine-driven lift devices or engine thrust for lift during these flight regimes and on nonrotating airfoil(s) for lift during horizontal flight.*

Propeller *means a device for propelling an aircraft that has blades on an engine-driven shaft and that, when rotated, produces by its action on the air, a thrust approximately perpendicular to its plane of rotation. It includes control components normally supplied by its manufacturer but does not include main and auxiliary rotors or rotating airfoils of engines*.

In addition to the above codified law, the FAA employs 'orders' that essentially instruct employees on policies and procedures. Of interest is FAA Order 8000.71 *Aircraft Make, Model, Series Taxonomy* with this seemingly little-known definition that is only slightly different than that for powered lift (PL).

Hybrid Lift *denotes a heavier-than-air aircraft that is supported at vertical takeoff, vertical landing, and low-speed flight by the dynamic reaction of the air against its rotors or thrust and in horizontal flight by the dynamic reactions of air against its wings (i.e., the tilt-rotor aircraft).*

This paper is not intended to challenge any of the above definitions, but to embrace as much as possible and suggest interpretation where appropriate. Also, this proposal does not presume to litigate new classes or categories for pilots or aircraft. We instead use terms 'tier' and 'box' because their meaning is clear yet independent of existing classification terminology. This proposal offers expanded language to clarify, and to fill voids.

Specifically, a void exists with the word 'rotor' as used above because there is no definition for an aviation rotor. While adequate in the past, new technology has enabled confusing possibilities. Another gap exists interpreting the word ‘principally’ used in the definitions of Rotorcraft, Helicopter and Powered Lift. The intent is not clear, and its presence triggers exceptions. This paper offers rational solutions to these voids.

It is also clear that formal rulemaking - new regulations in the code of federal register - is a markedly long-term process. It is the authors' hope that this proposal be considered, adapted as appropriate and then adopted as industry consensus. This approach allows authorities time to consider and codify. Perhaps a more flexible device such as FAA Order 8000.71 can fill voids in the interim.

3. Configuration-Based Taxonomy and Lexicon

The fundamental approach of this VTOL aircraft taxonomy is to focus on the devices that provide the capability to takeoff and land vertically (or nearly so in the case of gyroplanes). This taxonomy is structured broadly to accommodate any notional configuration and expand for novel technology if found lacking.

A consequence of focusing on vertical flight is that fixed wings are irrelevant to VTOL and low-speed capability, so are not significant. While certainly important for determining cruise performance, stability & control, and conventional runway performance, wings are ancillary to VTOL capability and are therefore treated as a lower-level descriptor rather than a key taxonomy discriminator. VTOL aircraft may have no wings at all or wing sizes across a spectrum. This approach bypasses the concern of wing size forcing an aircraft to change its class. A specific example is increasing the wing size of a lift-compounded Helicopter soon has it meeting the definition of a Powered Lift aircraft.

This paper introduces carefully-crafted terminology along the journey then compiles them for a convenient review. Much of the terminology used here [introduced using four-star bullets] should be familiar and easily adopted. Some language is entirely new but rationalized here for broad acceptance. This lexicon process begins with the following recommendation for aircraft propulsors:

❖ ***Propulsor*** – Device that generates thrust for lift, propulsion, or control applications.

A propulsor can
- but does not necessarily include the power source (powerplant).
- have a thrust line whose orientation varies relative to the airframe or is principally fixed.
- be ancillary - used only for control as in an anti-torque device - or
- be primary - used principally for lift or cruise thrust.

First Tier
With this aircraft propulsor definition in hand, the taxonomy's first level identifies fundamentally different propulsor applications
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❖ ***Lift Application –*** *Principally provide thrust to overcome gravity in low-speed flight and potentially for lift at higher speeds and to overcome drag in cruise flight.*

❖ ***Cruise Application*** – *Principally overcome forward drag in cruise flight.*

❖ ***Lift/Cruise Application*** – *Principally provide thrust to overcome gravity in low-speed flight and to over*come drag in cruise flight.

These three applications characterize the basic ways propulsors can be employed. The word 'principally' allows leeway to use some thrust for aircraft control (using auxiliary or primary devices).

Next, we advance simple terms distinguishing isolated applications vs. combinations.

❖ ***Pure*** - *Configurations employing a single primary propulsor application* (only Lift, only Cruise, or only Lift/Cruise).

❖ ***Thrust Compound –*** *Configurations employing multiple primary propulsor applications (Lift plus Cruise, Lift plus Lift/Cruise, or Lift/Cruise plus Cruise).*

The qualifier 'primary' used in both definitions allows using small ancillary propulsors for attitude control. Note that the Thrust Compound definition allows for combining any number of propulsor applications but the proposed taxonomy structure and the illustrations in this paper accommodate pairs of propulsors for brevity and simplicity. This still captures all configurations actually flown.

Figure 2 illustrates how the above comprise the VTOL aircraft taxonomy's top tier. The taller boxes capture the three pure applications while the three shorter boxes show pairwise combinations forming "+" compounds. As mentioned, all VTOL aircraft flown can be characterized at the top level by one of these six boxes.

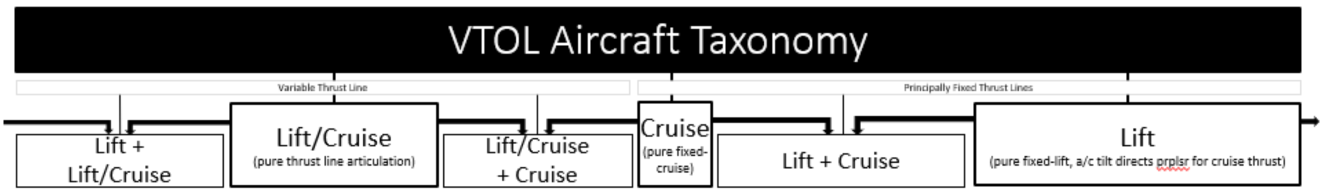

Figure 2, Taxonomy First Tier

This first level reveals two significant consequences . Pure Lift aircraft generate cruise thrust by tilting the airframe with its principally-fixed thrust line (long seen in helicopters and tail sitters). Pure Cruise aircraft with fixed-cruise propulsors cannot provide VTOL capability for heavier-than-air (HTA) craft, so the only VTOL aircraft that fit here are Lighter-than-air (LTA) airship configurations. Subsequent illustrations may recognize airships but reserve further discussion as out of scope.

A metaphor for these six types is that pure applications are akin to primary colors in a color wheel while the pairwise compounds are akin to secondary colors [a theme that returns later in this paper]. Also note this linear format could alternately be presented as a hexagon or circle by wrapping and connecting both ends.

<u>Second Tier</u>

The next level of the taxonomy adds basic lexicon for propulsor <u>installations</u>

- ***Lift** (L) – Fixed thrust line installation oriented principally vertical relative to the aircraft's rest position.*

A fixed-lift propulsor can either be a traditional rotor with a fixed mast orientation or another propulsor type such as a propeller, jet engine, or rocket, that modulates thrust along a fixed line.

- ***Cruise** (C) – Fixed thrust line installation oriented principally along the aircraft's forward flight direction.*

Fixed-cruise propulsor examples modulate thrust along a single axis - again usually employing some form of propeller, jet engine, or rocket. Whether or not it is practical, it is notionally possible to employ a rotor with a mast permanently oriented in the cruise direction.

There are three 'pure' means to achieve L/C capability: tilting the propulsor, vectoring the efflux (flow), or mechanizing the entire wing

- ***Tilt** (T) – Installation that can vary its thrust line by re-orienting the propulsor about the aircraft lateral axis.*

- ***Vector*** *(V) – Installation that can vary its thrust line by redirecting propulsor efflux.*

- ***L/C Wing*** *– Non-rotor, rigid or semi-rigid airfoil system that generates lift and forward thrust by its action* relative to the airframe.

Figure 3 shows these three pure L/C installation possibilities directly below the Lift/Cruise box.

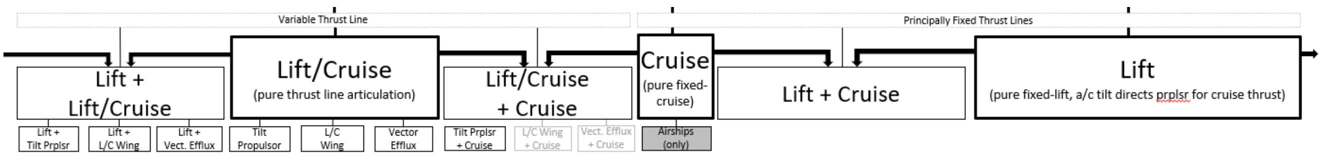

Figure 3, Possible Lift/Cruise Installations

Each of these pure L/C installations could be combined with a pure lift or pure cruise installation to form the compounds illustrated on the left side of Figure 3. This illustration uses light grey to denote notional configuration possibilities that do not (presently) have representative examples.

The linear format of Figure 3 shows the tiers. Completing the 2nd tier on the right side brings in rotorcraft. This invites definitions for an aviation rotor and its antithesis - the axial thruster. Axial thrusters exclude rotors, cycloids, articulating wings, and any sort of efflux vectoring or propulsor tilting.

- ***Axial Thruster*** *(AT) - Complete propulsion installation that generates thrust only along a single axis.*

As previously noted, various devices have been called rotors because there has been no commonly accepted definition. To provide clarity, this paper proposes the following for a proper aviation rotor.

- ***Rotor*** *- Rotating airfoil with ability to control and direct thrust along and off its spin axis.*

This definition was tailored to accommodate devices that have been accepted for modern certified rotorcraft. This stipulates an ability to direct off-axis thrust because this provides the control capability that modern rotorcraft need. Directing the rotor disc tilt generates a moment that pulls the rotor mast and in turn tilts the entire aircraft. Furthermore, the off-axis stipulation prevents considering propeller or tail rotor machines to be rotorcraft. It may be that such lack of clarity resulted in EASA's 2022 concerning proposal to re-define helicopters to limit them to only one or two rotors. Presumably intended to make room for novel multicopters, this disregarded previous multi-rotor designs and didn't recognize the distinction between proper rotors versus axial thrust propulsors.

On the other hand, this rotor definition purposefully does not stipulate helicopter-like collective pitch or cyclic control because simpler devices installed in gyroplanes have been accepted as rotorcraft (Figure 4).

Figure 4, Simple Gyroplane Rotor

While stipulating the disc tilt mechanization (cyclic vs. tilt hub) could be helpful for defining rotor subsets, the proposed aviation rotor definition is broad enough to bypass this question. This also does not stipulate flapping or other provisions for edgewise flow because it is trivial; all rotors must have some form of flapping (mechanical or structural) to balance lift between advancing and retreating blades. Nevertheless, the proposed concise definition could expand to explicitly require this feature.

'Rotorcraft' identifies an aircraft class and a pilot privilege (license) category. Within this privilege are classes for helicopter and gyroplane. Considering these and formal aircraft definitions leads to placing helicopters at the second tier under the Lift box and placing gyroplane and gyrodynes under the 'Lift+ Cruise' box (Figure 4). At this second tier, both gyro types are grouped together as thrust compound rotorcraft because they have some combination of rotor plus axial thruster (AT) for cruise.

Another 2nd tier configuration that fits under the Lift+Cruise box is one employing AT for both applications. This configuration has numerous old, new, and proposed examples (listed later).

Completing the taxonomy's second tier requires recognizing that another aircraft configuration does not fit within other second-tier boxes. Such aircraft have a pure, fixed-lift configuration without rotors, so cannot be helicopters. Because there is presently no name for such aircraft, proposed is

- ***Axicraft*** *- Aircraft that generates all low-speed lift and horizontal propulsive thrust through one or more axial thrusters, all with a fixed-lift orientation.*

Note that this definition intentionally does not stipulate the type of axial thruster; it may be any device that meets the AT criterion, including rockets, jets, and various rotating airfoil concepts. Figure 5 collates the above to present the VTOL aircraft taxonomy at the second tier.

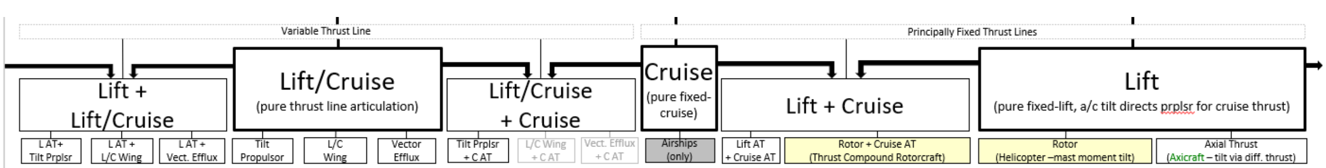

Figure 5, Taxonomy Second Tier

The Figure 5 taxonomy illustration

- Employs yellow shading to denote aircraft that qualify as rotorcraft.
- Shows 'L AT' and 'C AT' for compound installations. These can be further abbreviated as L and C because non-AT applications have names (rotor, cycloid, articulated, vectored, tilt).
- For brevity, reserves boxes for fixed-cruise rotors and for fixed-lift rotors compounded with the various L/C installations. This illustration can readily expand to accommodate these if any examples arise.

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Linguistic Fun Fact: The word 'helicopter' comes from Helico–pteron (helical-wing). The merged 'copter' term is therefore not tied to any specific kind of rotor or airfoil. Accordingly, an axicraft equipped with any type of rotating wings (vs. rockets or jets) can be further described as a multicopter, quadcopter, hexacopter, octocopter, etc.

Third Tier

The structure of Figure 5 can deepen to a third level by further refining the configuration options. Under the Lift/Cruise box, tilt propulsors can be either tilt rotor or tilt AT installations. This proposed taxonomy treats 'tilt wings' as a mere descriptive term outside the taxonomy structure because wing tilting is mostly just a means to tilt the propulsors. The vector efflux configuration can be mechanized via vectoring deflecting vanes (V_D) or vectoring nozzle (V_N) installations. Finally, the uncommon 'L/C Wing' configuration can be mechanized as either of two propulsor types

❖ ***Articulating*** *- Rigid or semi-rigid airfoil system that changes air momentum via flapping or other motions* [ornithopter]

❖ **Cycloid** - Rotating wing with ability to control and direct thrust normal to its spin axis.

Note that cycloids control force perpendicular to the spin axis unlike rotors that control force along and about the spin axis. At this 3rd tier, all six of these pure L/C configurations can be compounded with fixed-lift or fixed-cruise propulsors. The result is 18 configuration possibilities on the left side, as shown in Figure 6. Again, grey boxes indicate notional possibilities without examples.

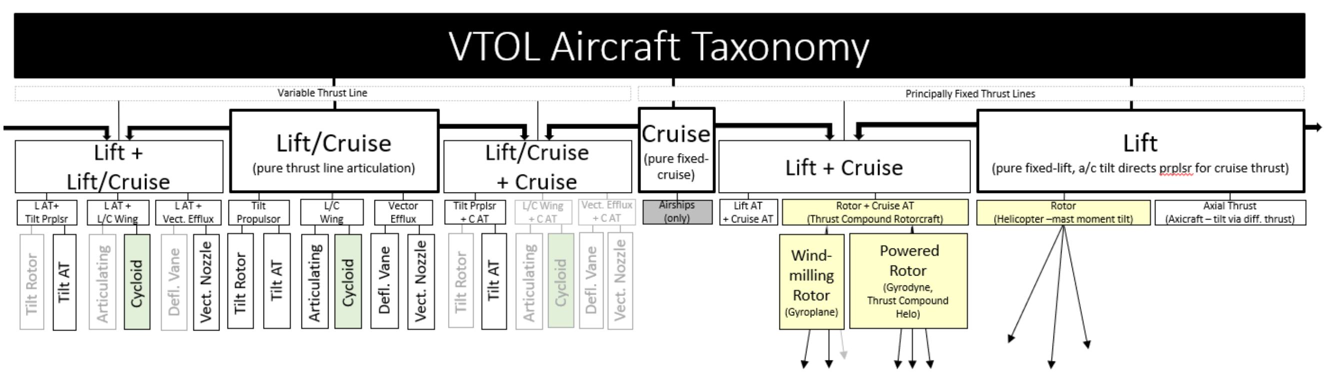


Figure 6, Three-Tier VTOL Aircraft Taxonomy

The right side of Figure 6 shows 3rd tier boxes capturing gyroplanes and gyrodynes. This illustration also uses an arrow quiver to denote the spectrum of possible wing sizes. Specifically, these show the wing lift fraction - compared to rotor lift - can vary anywhere from nil (left arrow) to 100% (right arrow). There is presently no clear boundary defining the middle arrow - where a fixed wing qualifies as a partial contributor to compound lift. For example, a helicopter stub wing used only to carry external stores would not qualify, but does it qualify if it has an airfoil profile that slightly unloads the rotor? The converse question applies to rotorcraft with a large fixed wing. Beyond what size does the aircraft no longer "*depend principally for its support in flight on the lift generated by one or more rotors"?*

Instead of proposing a clear boundary (e.g., partial lift ranges from 10% to 90% of cruise lift), this paper recommends sidestepping the question by offering a markedly simple interpretation of the established rotorcraft definition: *Rotorcraft means a heavier-than-air aircraft that* can *depend~~s~~ principally for its support in flight on the lift generated by one or more rotors.* With this sensible interpretation in place, a proper helicopter does not suddenly become a powered lift aircraft because the wing size crosses a threshold. The yellow boxes of Figure 5 would encompass all rotorcraft, regardless of any fixed-wing contribution.

Figure 6 also introduces green shading to identify aircraft that do not meet the criteria for rotorcraft (yellow shading) or powered lift (white). We need a new term that is broader than powered lift - one that encompasses all VTOL-capable aircraft not captured under the LTA or rotorcraft umbrellas.

- ***Verticraft*** *- HTA non-rotorcraft capable of vertical takeoff and landing*.

This intuitive and condensed term aligns with the EASA npa 22-06 definition: ***Vertical TakeOff and Landing-capable aircraft*** *is a power-driven, heavier-than-air aircraft, other than aeroplane or rotorcraft, capable of performing vertical take-off and landing by means of lift or thrust units used to provide lift during take-off and landing*.

Describing VTOL aircraft

Unless a broad, high-level description is desired, describe HTA aircraft at the lowest available tier.

For rotorcraft

Use the applicable definition for helicopter, gyrodyne, or gyroplane.

This proposed taxonomy uses the broad interpretation that a rotorcraft "can depend principally for its support in flight on the lift generated by one or more rotors."

For verticraft

Assume a pure application unless stated otherwise. There are eight basic installations

- Tilt Rotor (T_{Rtr})
- Tilt AT (T_{AT})
- Vector Deflect vanes (V_D)
- Vector Nozzle (V_N)
- Articulating (Art.)
- Cycloid (Cyc.)
- Lift AT (L) [pure application = axicraft]
- Cruise AT (C) [pure application = airship]

Identify compounds as 'plus' combinations of these eight basic installations. Of 28 notionally possible compound configurations, five have been realized [grey text denotes notional only].

L + C						
L + T_{AT}	T_{AT} + C					
L + T_{Rtr}	T_{Rtr} + C	T_{Rtr} + T_{AT}				
L + Art.	Art. + C	Art. + T_{AT}	Art. + T_{Rtr}			
L + Cyc.	Cyc. + C	Cyc. + T_{AT}	Cyc. + T_{Rtr}	Cyc. + Art.		
L + V_D	V_D + C	V_D + T_{AT}T	V_D + T_{Rtr}	V_D + Art.	V_D + Cyc.	
L + V_N	V_N + C	V_N + T_{AT}	V_N + T_{Rtr}	V_N + Art	V_N + Cyc.	V_N + V_D

Not only does this taxonomy accommodate these simple pairs of the eight basic installations, but the structure can also expand to include multiple "+" compounds. It can also expand beyond eight to add novel installations such as a fixed-cruise rotor (C_{Rtr}). Each addition would add another layer to the above [stepped] listing. Such structural flexibility should 'future-proof' this proposed approach to describing and classifying VTOL aircraft.

Note
1. Combining different L/C installations is especially notional and may be considered exotic.
2. This taxonomy and descriptive language accommodate but does not require the term 'powered lift'.

Additional Detail
Figure 6 captures the propulsor configurations comprising the taxonomy structure. Without adding more complexity or layers to this graphic, deeper fourth tier of information can be added by noting the propulsor count. Examples include 8L+2C, 6L+6L/C, R+2C, etc. For the sake of compactness, the Figure 6 format does not illustrate the extra granularity showing AT propulsor count or type. Type detail could be captured textually using common terminology.

4. Propulsor Lexicon

Describing AT propulsor types requires a simple taxonomy and lexicon for aeronautical propulsors. Figure 7 proposes this.

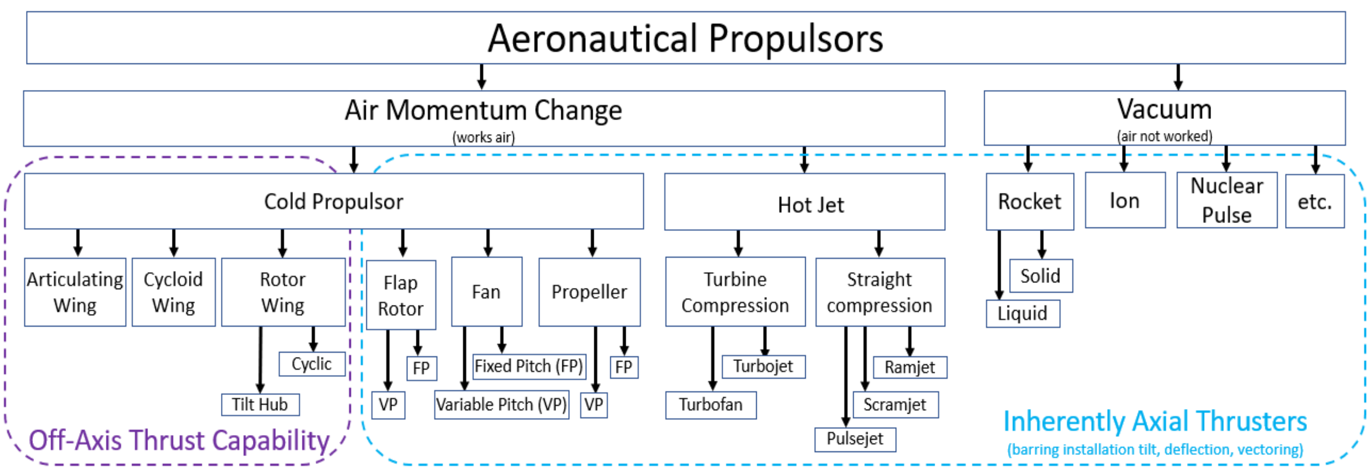


Figure 7, Aeronautical Propulsor Taxonomy

While most of the figure's terms need little discussion, a few useful new terms are proposed

- ***Cold Propulsor** – Device that generates thrust by changing ambient air momentum without its combustion.*

- ***Hot Jet** – Propulsor that generates thrust by changing ambient air momentum via its combustion.*

- ***Fan** – Rotating airfoil propulsor with solidity greater than 50% that generates axial thrust controlled by variation in blade pitch or speed.*

Less than 50% solidity (total blade area as a percent of swept area) is considered a propeller, with or without a duct or shroud.

For any aircraft description, a specific AT propulsor type could replace the broader 'AT' subscript. The same subscripts could append the L and C labels. Subscript abbreviations for hot turbojet, turbofan, and turboshaft types are Hjet, Hfan, and Hshf. A ducted fan is assumed unless specified as unducted (Udf). A variable-pitch prop is assumed unless specified as a fixed-pitch propeller (Fpp).

New is the box between rotor wing vs. fan and propeller-type propulsors. Here lie devices with flapping provisions to balance lift for sustained edgewise flow (like rotors) but generate only single-axis thrust (like fans and props). The majority of such devices are employed as and colloquially known as tail rotors. Although Igor Sikorsky often championed these as 'tail propellers', the CFR definition explicitly states a propeller "does not include main and auxiliary rotors or rotating airfoils of engines." To fill this name void, this paper offers a new term describing a thrust device whose disc can operate edgewise to the airflow and can be applied for anti-torque, for lifting a multicopter, or for other purposes not requiring disc tilt control.

- ***Flap Rotor*** *(or flap-only-rotor) - Rotating airfoil with provisions for sustained edgewise flow and without ability to direct thrust off its spin axis.*

Unlike the preceding definition for a 'proper' rotor, flap rotor stipulates sustained edgewise flow to distinguish this device from propellers and fans. This term accommodates colloquial use of 'tail rotor' but it is still not a proper rotor. Perhaps surprisingly, this definition is somewhat broad. Potentially refining descriptors include:

- Fixed pitch vs. variable pitch
- Powered - describes conventional anti-torque and novel vertical lift applications.
- Windmilling - describes primitive applications.

Windmilling 'flap rotors' were used in the earliest rotorcraft - gyroplanes. Examples include the Cierva C.6 (1924) and the Pitcairn PA-18 (1932). These rotating wings did not have off-axis thrust control, nor collective pitch control, nor were they powered. They only had provisions for flapping and (later) lead-lag compensation and could only autorotate. As evidenced in Figure 8, these aircraft could not use the rotors to control pitch and roll and instead relied on conventional tails and wings (or free-standing ailerons as in the C.6).

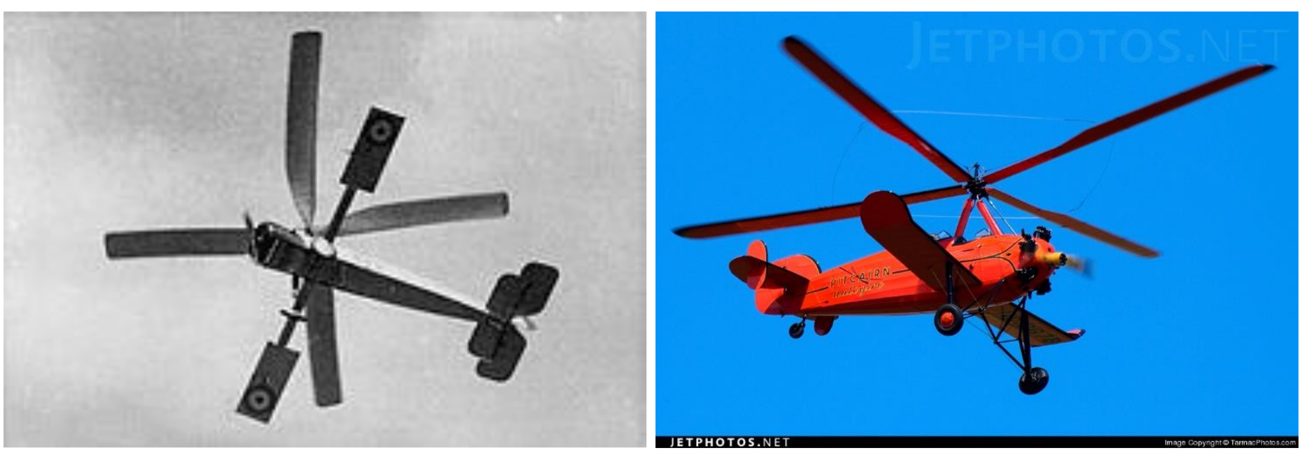


Figure 8, Primitive Rotorcraft

Although considered rotorcraft a century ago, we do not presume the severely limited C.6 and PA-18 control capabilities meet sensibilities appropriate for a modern rotorcraft. They can however be easily accepted as ‘grandfathered’ exceptions to the rotorcraft class. In fact, the first rotorcraft type certificate went to the Pitcairn PCA-2.

5. VTOL Aircraft Examples

Following are VTOL aircraft examples placed within the rotorcraft, powered-lift, and proposed taxonomy structures. Some flew many years ago, some are new, and some have flown only in small scale, showing at least some viability if not practicality. These include bracketed text showing the (4^{th} tier) propulsor count and (subscripted) propulsor types.

Abbreviations not previously noted include

CCR = coaxial counter rotating

* = Auxiliary thrust device(s) needed for control

= Backpack rig – not freestanding

^ = kinesthetic 'weight shift' CG control

Italicized are helpful descriptors outside the taxonomy structure.

<u>Rotorcraft Examples</u>

Helicopter

This taxonomy encompasses all VTOL aircraft but does not list traditional helicopter examples because these lay outside this paper's scope. Listed instead are basic rotor configurations and examples of winged helicopters. A single classic lift rotor is assumed unless otherwise noted.

[1x]
[CCR]
[2x Mesh]
[2x Tandem]
[2x Transverse]
[3+ Multicopter]

Partial Wing

Boeing Vertol 347 [2Tandem]
MBB BO105 HGH [1]
Sikorsky S-67 [1]

Cruise-Wing Helisitter (helicopter-*tailsitter)*

Boeing Heliwing [2]

Gyrodyne

Sikorsky S-97 [CCR + C_{Prop}]
Boeing SB-1 [CCR + C_{Prop}]

Partial Wing

Fairey Rotodyne [*tip jet* + $2C_{Prop}$]
McDonnel XV-1 [*tip jet* + C_{Prop}]
Kamov Ka-22 [2Trans. + $2C_{Prop}$]
Jaunt [+ $2C_{Prop}$]
Piasecki PA-890, X-49, 16H [+ C_{Prop}]
Lockheed AH-56 [+ C_{Prop}]
Kamov V-100 [+ C_{Prop}]
Fairey FB-1 [+ C_{Prop}]
Sikorsky NH-3A (S-61F) [+ $2C_{Hjet}$]
Lockheed XH-51A [+ C_{Hjet}]
Kaman UH-2 [+ C_{Hjet}]

Cruise-Wing Gyrodyne (CWG)

Sikorsky S-72 [*Stop Rtr* + $2C_{Hfan}$]
Boeing X-50 [*Stop Rtr* + C_{Prop}]

Gyroplane

Cierva C.4, C.6 [Flap Rtr + C_{Fpp}]
CarterCopter [+ C_{Prop}]
McCulloch J-2 [+ C_{Prop}]
Wilford WRK [+ C_{Fpp}]
MagniGyro M16 [+ C_{Fpp}]
Wallis WA-116 [+ C_{Fpp}]

Partial Wing

Pitcairn PCA-2 [Flap Rtr + C_{Fpp}]
Pitcairn PA-18 [Flap Rtr + C_{Fpp}]
Cierva C-19 Mk I [Flap Rtr + C_{Fpp}]
Cierva C-19 Mk V [+ C_{Fpp}]

Powered Lift Examples

<< Lift/Cruise >>

Tilt Rotor (T_{Rtr})

Transcendental 1G [2T_{Rtr}, *shaft*]
Bell XV-3 [2T_{Rtr}, *shaft*]
Leonardo AW-609 [2T_{Rtr}]
Bell XV-15 [2T_{Rtr}]
Bell V-280 [2T_{Rtr}]
Bell Boeing V-22 [2T_{Rtr}]

Tilt AT (T_{AT})

Curtiss-Wright X-100 [2T_{Prop}*]
Curtiss-Wright X-19 [4T_{Prop}]
Dornier Do-29 [2T_{Prop}]
Joby S4 [6T_{Prop}]
Lilium [36T_{Fan}]
Doak 16 VZ-4 [2T_{Fan}*]
Aurora XV-24 [24T_{Fan}]
Nord N 500 [2T_{Fan}*]
Bell 65 ATV [2T_{Hjet}]

Tilt Wing

Transcend VY 400 [2T_{Prop}*]
Vertol VZ-2 [T_{Prop}*]
LTV XC-142 [4T_{Prop}*]
Canadair CL-84 [2T_{Prop}*]
Hiller X-18 [4T_{Prop}, CCR*]
NASA GL10 [10T_{Fpp}]
Verdego [8T_{Fpp}]
Airbus Vahana [8T_{Fpp}]
Dufour Aero2 [4T_{Fpp}*]

Deflect Vane (V_D)

Fairchild VZ-5 [4V_{DProp}*]
Robertson X-1 [2V_{DProp}]
Ryan VZ-3 [2V_{DProp}*]

Tailsitter

Convair XFY-1 [L_{Prop}]
Lockheed XVF-1 [L_{Prop}]

Vector Nozzle (V_N)
Bell X-14 [2V_{NHjet}]
Yak 36 [2V_{NHjet}]
H.S. Harrier [V_{NHfan}]
Boeing X-32B [V_{NHfan}]
Tailsitter
Ryan X-13 [V_{NHjet} *]

Articulating
Aerovironment NAV [Art.]

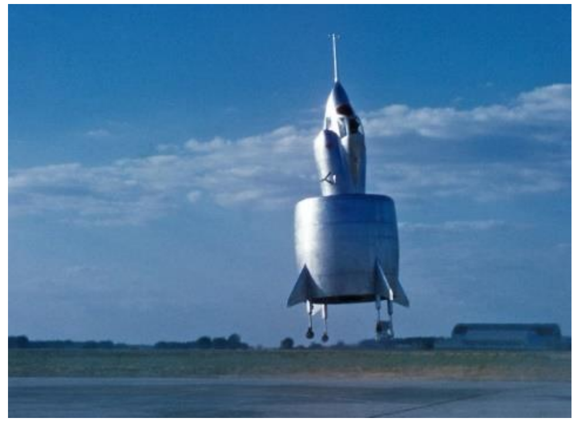
<< Lift + Lift/Cruise >>
Lift - plus - Tilt AT (L+T_{AT})
Airbus CityAirbus [6L_{Prop} + 2T_{Prop}]
Wisk G6 [6L_{Fpp} + 6T_{Prop}]
Archer [6L_{Prop} + 6T_{Prop}]
XTI Tri Fan [L_{Fan} + 2T_{Fan}]

Lift - plus - Vectored Nozzle (L+V_N)
VFW VAK 191 [2L_{Hjet} + V_{NHfan}]
Lockheed F-35B [L_{Fan} + $V_{N\ Tfan}$]
Dornier Do-31 [8L_{Hjet} + 2V_{NHfan}]
Yak 38M [2L_{Hjet} + V_{NHfan}]
Yak 141 [2L_{Hjet} + V_{NHfan}]
EWR VJ101 [2L_{Hjet} + 4V_{NHjet}]
Lockheed XV-4A [2$_{Hjet}$, L or V_N*]
Lockheed XV-4B [4L_{Hjet} + 2V_{NHjet}*]

<< Lift/Cruise + Cruise >>
Tilt AT - plus - Cruise (T_{AT}+C)
Curtiss X-19 [4T_{Prop} + 2C_{Hshf}]

<< Lift + Cruise >>
Lift AT - plus - Cruise AT (L+C)
Eve [8L_{Prop} + 2C_{Fpp}]
Beta Alia [4L_{Prop} + C_{Fpp}]
Aurora PAV [8L_{Prop} + C_{Fpp}]
Elroy Chapparal [6L_{Prop} + C_{Fpp}]
Vanguard Omniplane [2L_{prop} + C_{Prop}]
Dassault Mirage IIIV [8L_{Hjet} + C_{Hfan}]
Dassault Balzac V [8L_{Hjet} + C_{Hjet}]
Short SC1 [4L_{Hjet} + C_{Hjet}]
Ryan XV-5A [3L_{Fan} + 2C_{Hjet}*]

<u>Axicraft Examples</u>
Axisitter
Bell APT [4L_{Fpp}]
NASA Puffin [2L_{Fpp}]
Opener Blackfly [8L_{Fpp}]
Bachem Ba 349 [4L_{Fpp}]
Rossy Jet Wingpack# ^ [4L_{Hjet}]



Figures 9a, b, c; Deflected Vane Examples

MonoThruster

Hiller VZ-1^ [CCR_{Prop}]
De Lackner HZ-1^ [*CCR*$_{Prop}$]

Multithruster

Lift Hexa [$18L_{Fpp}$]
Volocopter Volocity [$18L_{Fpp}$]
eHANG 216 [$16L_{Fpp}$]
Boeing CAV [$12L_{Fpp}$]
Kittyhawk Flyer[$10L_{Fpp}$]
Jetson [$8L_{Fpp}$]
Copterpack# ^[$2L_{Fpp}$]
Solo Trek XVF [$2L_{Fan}$]
Zapata Flyboard^ [$5L_{Fan}$]
Martin jetpack [$2L_{Fan}$]
Airborne Air Commuter [$4L_{Fan}$]
Jetpack JB11# ^[$6L_{Hjet}$]
Jet Pack H202# ^ [$2L_{Rkt}$]
Bell Rocket Belt#^ [$2L_{Rkt}$]
Kaman Kargo [$4L_{Flap\ rtr}^{+}$]

<u>Bastard Examples</u>

Without rotor, full wing, or pure AT - these don't qualify as rotorcraft, powered-lift, or axicraft

<< Lift/Cruise >>

Deflect Vane (V_D)

SNECMA C450 [V_{DHjet}], Figure 9a
Piasecki Air Scout [$2V_{DFan}$], Figure 9b
Aurora Goldeneye [V_{DFan}], Figure 9c

Cycloid

CycloTech [4Cyc.], Figure 10a

<< Lift + Lift/Cruise >>

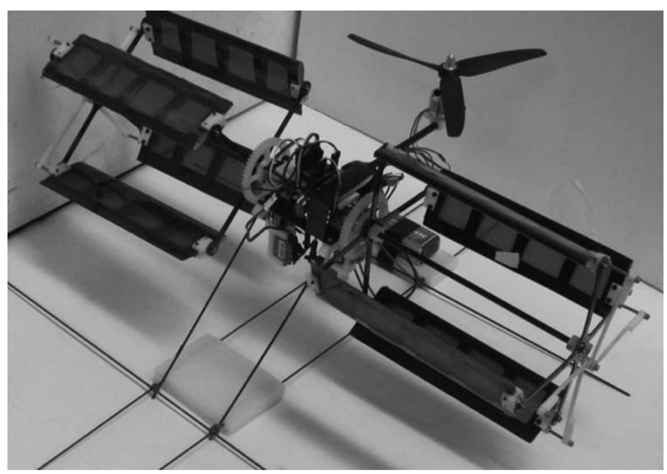
Lift + Cycloid

Rehm Cycloplane
[L_{Prop} + 2Cyc.], Figure 10b

<< Lift/Cruise + Cruise >>

L/C + Tilt AT

Bell X-22 [$4T_{Hfan}$ + $4C_{Hshf}$]



Figures 10a, b; Cycloid Examples

As previously noted, powered lift, axicraft, and even these otherwise homeless bastard examples lie under the 'verticraft' umbrella. All examples, notes, and a legend are presented in the linear format of Figure 11.

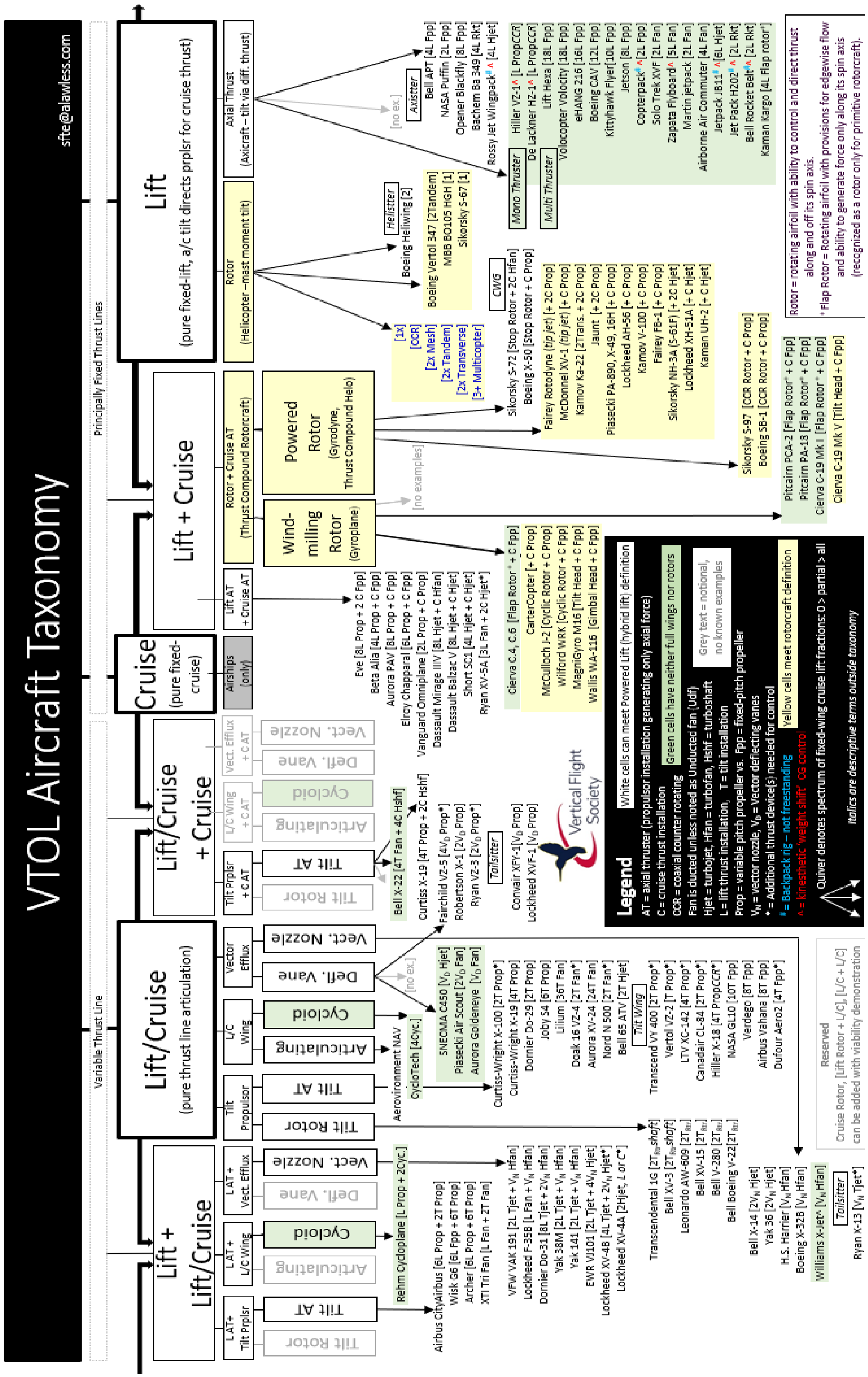


Figure 11, Proposed Taxonomy - Linear Format with Examples

6. TAXONOMY STRUCTURE SUMMARY

Ultimately, verticraft can be classified using the eight pure installations (L, C, T_{Rtr}, T_{AT}, V_D, V_N, cycloid, articulating) and their appropriate "plus" compounds. The linear format of Figure 10 clearly shows the taxonomy structure. Depending on the level of granularity desired, VTOL aircraft can be identified at a high level (first tier) all the way down to a fourth tier and further embellished with propulsor details. Figure 10 reserves C_{Rtr} installations and exotic L/C + L/C compounds but still presents 23 notionally possible 'boxes.' While this variety can be overwhelming, it provides all the more reason to establish the language and structure to describe distinguishing features.

There is no proposal or desire to use this taxonomy to instate multiple new airworthiness rulesets (e.g. Part 24, 26...). Nevertheless, an expanded lexicon allows industry, academia, and regulators to effectively communicate key features. This framework can be used to identify common features that merit common standards for showing compliance to broad airworthiness rules.

The formal powered lift definition was well-suited for the needs at the time of its writing. With sufficient clarity, it separated traditional rotorcraft and their flight characteristics from aircraft that relied on a fixed wing for cruise flight. Figure 10's white boxes and white text background show that powered lift aircraft dominate verticraft population. Nevertheless, the figure also illustrates the exceptions that cause concern when proposing new rules explicitly for powered lift aircraft. Green backgrounds show aircraft that don't qualify as PL because they employ technologies and configurations outside the PL scope.

Another concern highlighted in Figure 10 is the mismatch between the yellow (rotorcraft) background in the helicopter and gyrodynes boxes versus their subordinate white (PL) examples - imposed by having large cruise wings. This paper offers the preceding interpretation to avoid this dilemma.

Alternate Accommodations

If rotorcraft and powered lift definitions are enforced and strictly interpreted as written, then this paper offers the following additional language and taxonomy accommodations to promote symmetry and avoid confusing self-conflict among rotorcraft.

1) At the 2nd tier, replace the helicopter box with new a definition that accommodates traditional and cruise-wing helicopters

- ***Helicraft** - Aircraft that generate all low-speed lift and horizontal propulsive thrust through one or more fixed-lift rotors.*

2) Move the helicopter box to the 3rd tier, under helicraft.

3) Also under helicraft, adjacent to the helicopter box, inject a new box for cruise-wing aircraft with lift rotors

- ***Helisitter** - Helicraft with wings that* (lift enough to) *qualify as powered-lift aircraft.*

4) At the 3rd tier, under 'Rotor + Cruise AT' inject a new box for full-wing types. (previously described as cruise wing gyrodynes, this name is ineligible with strict PL and rotorcraft interpretations.)

- ***Gyrositter**- Gyrodyne with wings that* (lift enough to) *qualify as powered-lift aircraft.*

5) At the third tier under Axicraft, inject a new box for pure fixed-lift AT aircraft with cruise wings.

❖ ***Axisitter*** - *Axicraft with wings that* (lift enough to) *qualify as powered-lift aircraft.*

Figure 12 illustrates how the above accommodations deconflict classifications.

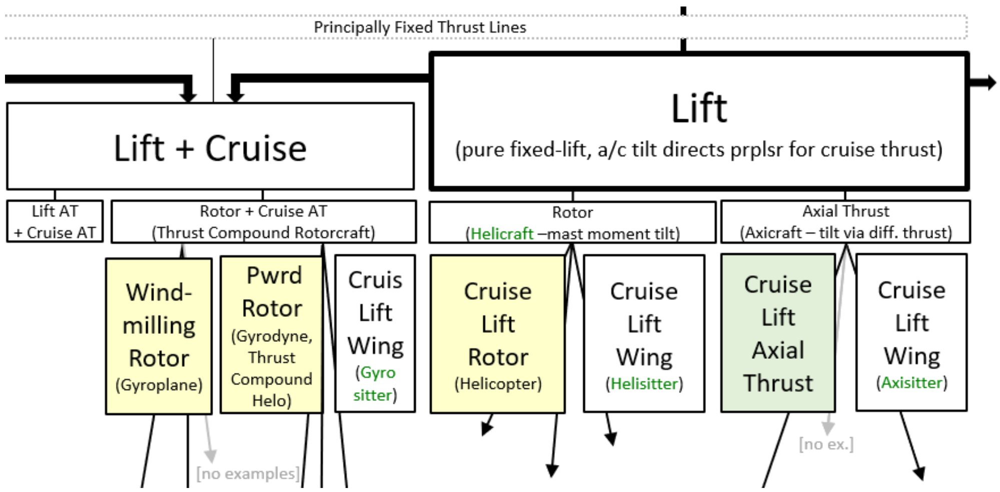


Figure 12, Taxonomy Accommodation for Strict PL and Rotorcraft Interpretations

The above accommodating definitions would require determining what "lift enough" means. This would be some fixed-wing amount that crosses the threshold into powered lift. Although outside this paper's intent and scope, such a threshold could be established as a lift fraction at the cruise design point, as a ratio of fixed-wing to disc area, by marked performance or flight characteristic changes, or by some other means.

7. Presentation Formats - Re-inventing the Wheel

There are three basic approaches to illustrating the recommended taxonomy. All presented here capture the eight pure installations and the compounds using Lift or Cruise installations (but not L/C + L/C combinations). Figure 10 clearly shows tiers and the configuration taxonomy in a familiar organizational format and allows listing numerous examples. This format is somewhat repetitive and relies on [bracketed] text to add 4th tier information about the propulsor count and propulsor types. Fifteen of the 23 lowest level boxes have examples that flew.

Figure 13 provides a second illustration option using a matrix format to graphically present both the configuration and propulsor taxonomies and their combinations. Black cells block out impossible combinations, grey cells depict notional but unfilled possibilities, and white cells have aircraft example within that particular intersection. This format better illustrates possible configuration and propulsor combinations but does not readily show more than one example. Of course, digital versions of this presentation could easily capture any number of examples at any intersection.

Category				Off-Axis Thrust Capability				Inherently Axial Thrusters														
1st level				Air Momentum															Vacuum			
	2nd level			Cold Propulsor									Hot Jet						Rocket		Ion	Nuclear
		3rd level		Artic. Wing	Cycloid Wing	Rotor Wing		Flap Rotor		Fan	Propeller		Turbine			Straight Compression			Solid	Liquid		
			4th level			Cyclic	Tilt Hub	Fixed Pitch	Adj. Pitch		Fixed Pitch	Adj. Pitch	Turbo jet	Turbo fan	Turbo shaft	Ram jet	Scram jet	Pulse jet				
Lift [pure]	Axicraft		#						Kargo	Trek XVF	Volocity	VZ-1	JB11							BA-349		
	Helicopter		#			many	?															
Lift + Cruise	Rotor + Cruise	Gyroplane	#			WRK	many	C.4 L			many											
		Gyrodyne	#			many					Rotodyne		XH-51A									
	L AT + Cruise		#								PAV	AH-56	Balzac V	Mir. IIIV								
Lift/Cruise + Cruise	L/C Wing + Cruise AT	Articulating + C	#																			
		Cycloid + C	#																			
	Tilt Propulsor + Cruise AT	Tilt AT/Wing + C	#							X-22 [T]		X-19 [T]			X-22 [C]							
		Tilt Rotor + C	#																			
	Vectored Efflux + Cruise AT	Defl. Vane + C	#																			
		Vect. Nozzle + C	#																			
Lift/Cruise [pure]	L/C Wing	Articulating	#	NAV																		
		Cycloid	#		Cyclo Tech																	
	Tilt Propulsor	Tilt AT/Wing	#							Lilium	Vahana	CL-84	Bell 65									
		Tilt Rotor	#			V-22	?															
	Vectored Efflux	Defl. Vane	#							Air Scout		XVF-1	C450									
		Vect. Nozzle	#										X-14	Harrier								
Lift + Lift/Cruise	Lift AT + L/C Wing	L + Articulating	#																			
		L + Cycloid	#								cycloplane											
	Lift AT + Tilt Propulsor	L + Tilt AT/Wing	#							XTI Trifan	Wisk G6 [L]	Wisk G6 [T]										
		L + Tilt Rotor	#																			
	Lift AT + Vectored Efflux	L + Defl. Vane	#																			
		L + Vect. Nozzle	#							F-35B [L]			VJ101	F-35B [V]								

Figure 13, Proposed Taxonomy - Matrix Format

A popular illustration capturing 20th Century V/STOL aircraft configurations resulted from considerable thought, and the Vertical Flight Society widely promoted the now classic 'VFS Wheel' shown in Figure 14. Nevertheless, just as the advent of newer technologies and capabilities calls for this new taxonomy and terms, it calls for re-inventing the wheel.

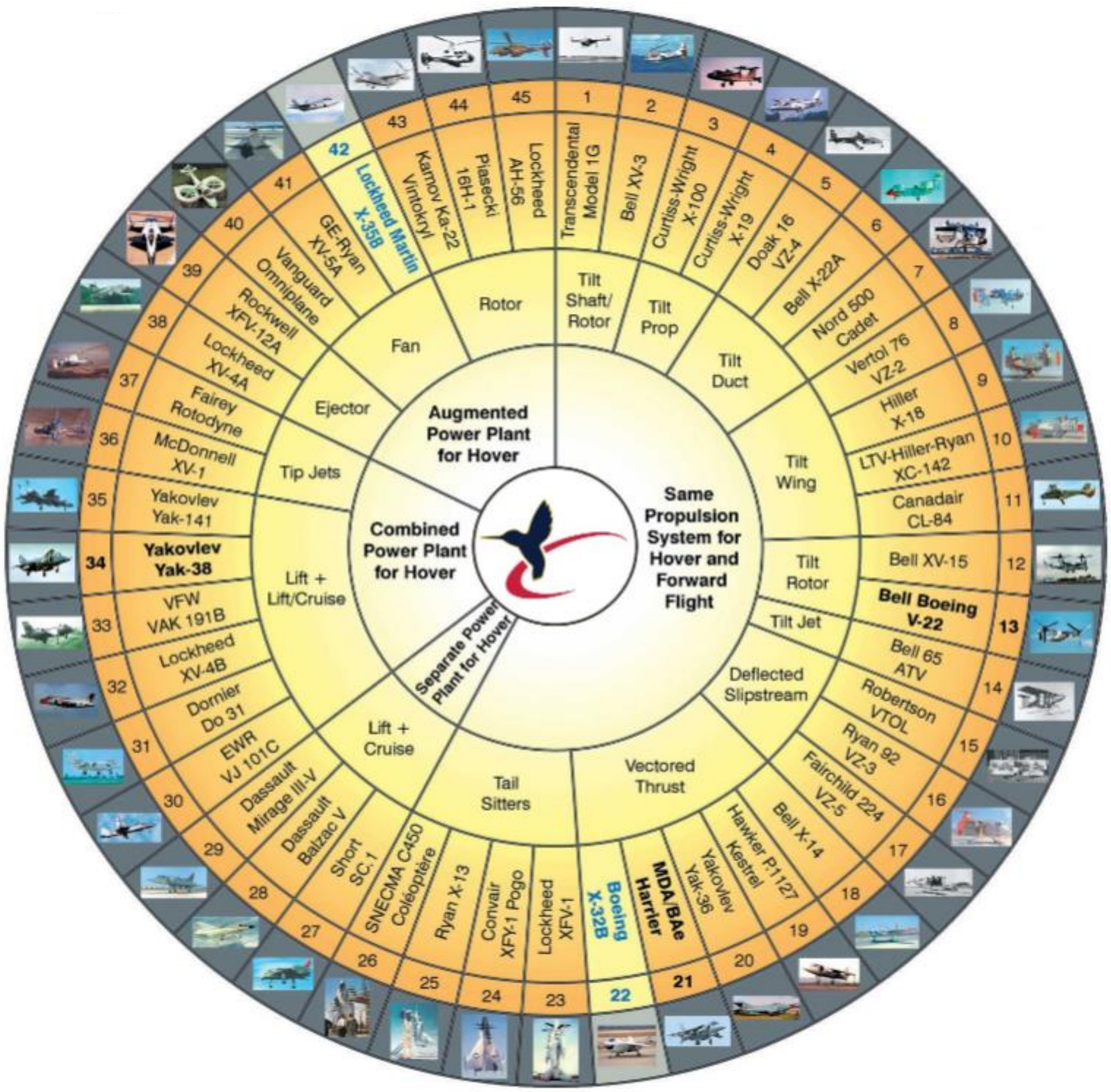


Figure 14, The VFS Wheel - 20th Century VSTOL Aircraft <https://vtol.org/vstol/wheel.htm>

Reflecting the thinking behind the taxonomy structure, Figure 15 begins laying out a third format that differently illustrates the same pure applications and installations identified earlier:

- ∇ Fixed Lift: Rotor (helicopter) or Axial Thrust (axicraft)
- ∇ Fixed Cruise: Axial Thrust [fixed-cruise rotor reserved]
- ∇ Lift/Cruise: Tilt Propulsor (Rotor, AT), Vector Efflux (Defl. vane, Vect. nozzle), L/C Wing (Cycloid, Articulating)

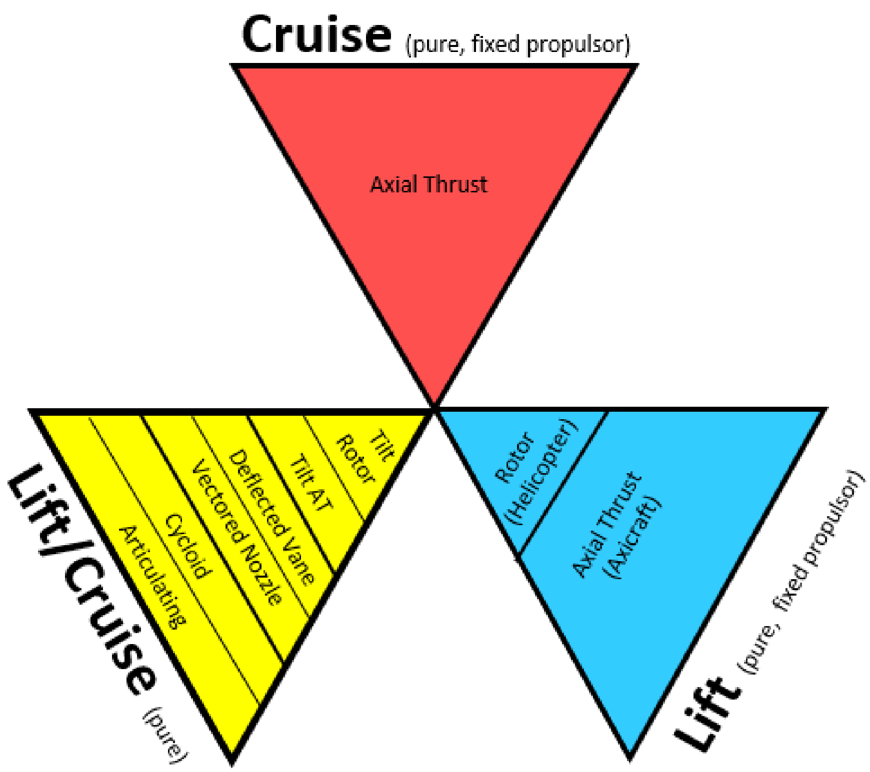


Figure 15, Proposed Taxonomy - Pure Application Triangles

Helicopters fit within the inner blue triangle while tilt rotor PL aircraft fit within the inner yellow triangle. Other pure applications fit within one of the blue or yellow trapeziums. Within each triangle, thick lines distinguish 2nd tier configurations while thin lines separate 3rd tier configurations. Recall that only airships fit within the red (fixed-cruise) triangle and are outside this paper's scope.

Considering that compounds are some combination of pure applications, Figure 16 simply extends all three triangle lines to cleverly capture all configuration possibilities at the third tier. Every compound fits within one of the resulting parallelograms. Without the repetition of Figures 11 or 13, the resulting grand triangle compactly includes spaces for compounding fixed-lift rotors with various L/C applications. The use of color is not necessary but is visually enhancing and recalls the earlier point that pure and compound applications are akin to primary and secondary colors.

Going beyond the first three configuration tiers, Figure 17 adds more granularity by injecting thick and thin dashed lines to distinguish propulsion types at mid and detailed levels. There are too many types to practically present all in this format, so the authors reserved some propulsor type descriptors.

Also, because HTA VTOL aircraft don't exist in a pure cruise configuration, Figure 17 greys out this triangle. Combined with carefully considered layout, color, and labeling edits, a format illustrating the VTOL taxonomy can be in the shape of a 'V.' Each space within this V pictorially shows where an aircraft sits at the 1st tier (color), 2nd tier (labels between thick lines), and 3rd tier (labels between thin lines). Placement between dashed lines provides propulsor details.

The authors recommend the compact and elegant V of Figure 17 to replace the V/STOL wheel.

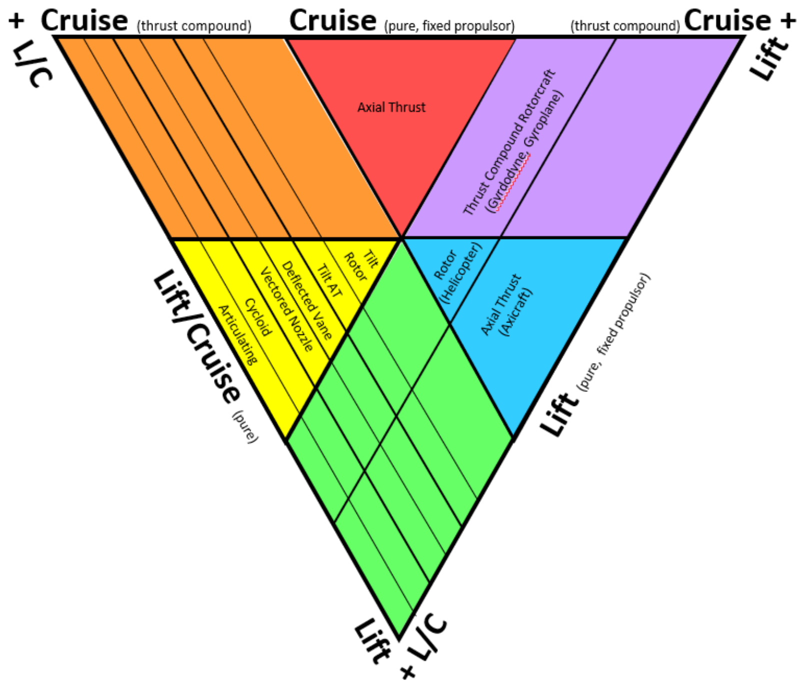


Figure 16, Proposed Taxonomy - Configuration Triangle

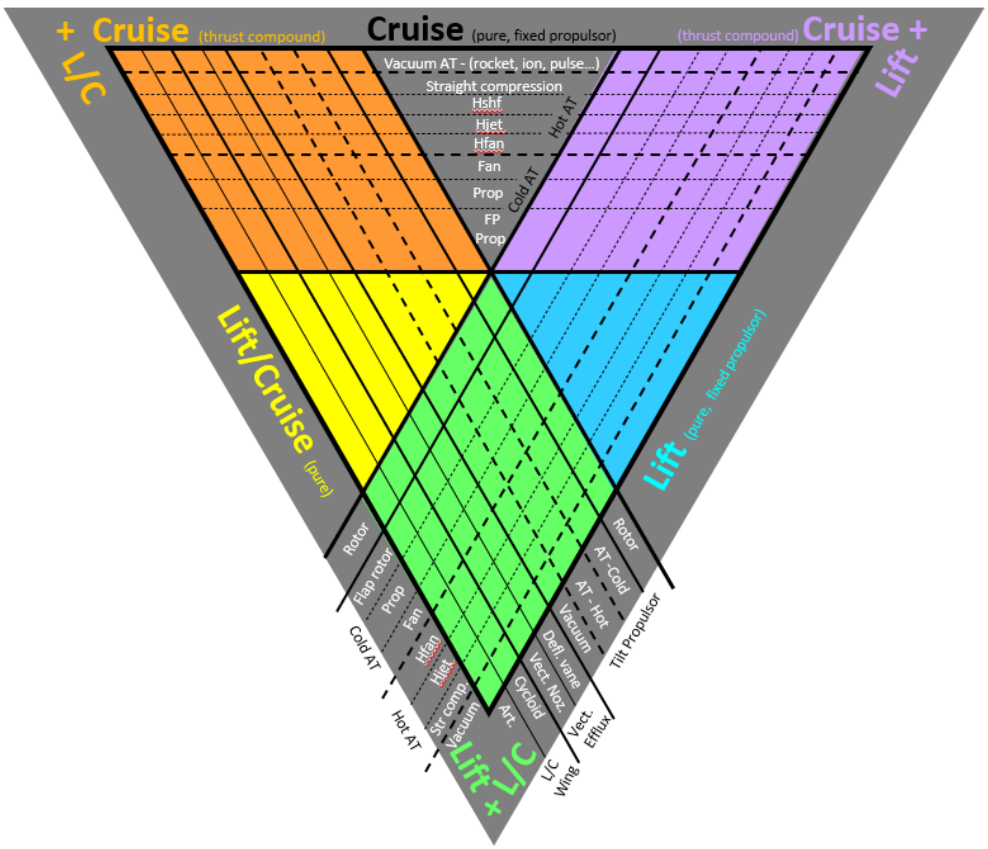


Figure 17, Proposed Taxonomy - Configuration and Propulsor V

All formats presented here ignore exotic [L/C +L/C] configurations and accommodate only simple compounds - those with a single "+". While the illustrations can change to increase or decrease detail and add or remove installations such as a fixed-cruise rotor (C_{Rtr}), adjustments can wait until settling this proposed taxonomy and terminology.

8. Expected Debate

The authors consider all recommendations here to be readily acceptable but expect and invite debate to ensure broad industry acceptance of the structure, concepts, definitions, and new terms. Such acceptance would render this work a fait accompli that then allows regulators to adopt it at the speed of rulemaking. The most anticipated discussion topics include the following four formal definitions and two interpretations

- ☐ **Verticraft definition**. With PL limitations, what language will regulators use to capture VTOL aircraft not already under a classification umbrella?

- ☐ **Axicraft definition**. Respecting established definitions for PL and rotorcraft leaves a taxonomy void for aircraft without rotors or wings.

- ☐ **Rotor definition**. CFRs refer to 'rotor' when defining rotorcraft, but don’t define an aviation rotor. A proper definition should not 'rock the boat' of accepted usage but instead reflect historically-used devices that lift and control helicopters, gyroplanes, and gyrodynes.

- ☐ **Flap Rotor definition**: The definition for a 'proper' rotor leaves a void when describing rotary wing devices such as so-called tail rotors. Should the term instead be relegated to be just an informal descriptor under proper rotors, fans or propellers?

- ☐ **Rotorcraft interpretation**. In lieu of setting wing size threshold beyond which a rotorcraft is no longer a rotorcraft, can we interpret the rotorcraft definition as "... aircraft that <u>can</u> depend principally for its support in flight on the lift generated by one or more rotors“?

- ☐ **'Principally' Threshold interpretation**. If only a strict rotorcraft and PL interpretation is allowed, then we should establish the point beyond which a fixed wing is big enough that it no longer “…depends principally for its support in flight on the lift generated by one or more rotors.“ This might be defined by some combination of
    - Fraction of wing contribution to lift, (e.g. 50%, 75%, 90%)
    - Wing/Disc area ratio (e.g. ¼, 3/8, ½)
    - RPM or thrust drop
    - Change in trim or flight characteristics

For convenient review, the terms proposed in this paper is collated and repeated below.

Articulating - Rigid or semi-rigid airfoil system that changes air momentum via flapping or other motions (ornithopter).

Axial Thruster (AT) - Complete propulsion installation that generates thrust only along a single axis.

Axicraft - Aircraft that generates all low-speed lift and horizontal propulsive thrust through one or more axial thrusters, all with a fixed-lift orientation.

Axisitter - Axicraft with wings that (lift enough to) qualify as powered-lift aircraft.

Cold Propulsor – Device that generates thrust by changing ambient air momentum without its combustion.

Cruise Application – Principally overcome forward drag in cruise flight.

Cruise (C) – Fixed thrust line installation oriented principally along the airframe's forward flight direction.

Cycloid - Rotating wing with ability to control and direct thrust normal to its spin axis.

Fan – Rotating airfoil propulsor with solidity greater than 50% that generates axial thrust controlled by variation in blade pitch or speed.

Flap [only] Rotor - Rotating airfoil with provisions for edgewise flow and without ability to direct force off its spin axis.

Helicraft - Aircraft that generate all low-speed lift and horizontal propulsive thrust through one or more fixed-lift rotors.

Helisitter - Helicraft with wings that (lift enough to) qualify as powered-lift aircraft.

Hot Jet – Propulsor that generates thrust by changing ambient air momentum via its combustion.

Lift Application – Principally provide thrust to overcome gravity in low-speed flight and potentially for lift at higher speeds and to overcome drag in cruise flight.

Lift (L) – Fixed thrust line installation oriented principally vertical relative to the aircraft's rest position.

Lift/Cruise Application – Principally provide thrust to overcome gravity in low-speed flight and to overcome drag in cruise flight.

L/C Wing – Non-rotor, rigid or semi-rigid airfoil system that generates lift and forward thrust by its action relative to the airframe.

Propulsor – Device that generates thrust for lift, propulsion, or control applications.

Pure - Configurations employing a single type of primary propulsor.

Rotor - Rotating airfoil with ability to control and direct thrust along and off its spin axis.

RCCW - Rotor + Cruise + Cruise Wing aircraft with wings that (lift enough to) qualify as powered-lift aircraft.

Tilt (T) - Installation that can vary thrust its line by re-orienting the propulsor about the a/c lateral axis.

Thrust Compound – Configurations employing multiple primary propulsor types.

Vector (V) - Installation that can vary its thrust line by redirecting propulsor efflux.

Verticraft - HTA non-rotorcraft capable of vertical takeoff and landing.

9 ACKNOWLEDGEMENTS, REFERENCES

The authors thank their professional communities for input to this work.

References

Title 14 CFR, Chapter I, Subchapter A, Part 1
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10 AUTHOR BIOGRAPHIES

Society of Flight Test Engineers (SFTE) Fellow Al Lawless has been continuously active since 1984. Al's FTE experience encompasses time in the USAF [HH-60, B-52, F-16, Agility Research], academia [National Test Pilot School instructor, textbook author, Chief of Academics], FAA certification [Cessna Sovereign, CJ1+; Honda HA-120], international certification [Grob SPn], and the Perlan 2 high altitude sailplane project. He built up flight test departments [Grob Head of FT, Honda Chief FTE] and is a Flight Analyst DER for Part 23 and Part 25 aircraft. Al is a Multi-engine Commercial Instrument pilot, glider, motor glider pilot, and aircraft owner. He served as SFTE Antelope Valley Chapter Vice President and President; Board Director, Technical Council Chairman from 2004-2020, and now Chairs the E-VTOL FTC. In recognition for launching the SFTE Reference Handbook and other initiatives over years, his SFTE honors include AV Chapter FTE of the Year and the Directors', Kelly Johnson, and James McDonnell awards. Now the Flight Test SME for Aurora Flight Sciences and a Boeing Associate Technical Fellow, he is also a member of VFS and the BT&E Flight Test Board where he contributes best FT practices for future testers.

Dan Newman is a Boeing a Senior Technical Fellow and serves as Chief Engineer for Advanced Vertical Lift. He was previously a Program Manager at the Defense Advanced Projects Research Agency (DARPA). He is a Fellow of the American Institute of Aeronautics and Astronautics (AIAA), and a Technical Fellow and an Honorary Fellow of the Vertical Flight Society (VFS).   As VFS Technical Director, he was an architect of the Transformational Vertical Flight Workshops that catalyzed the urban air mobility and electric VTOL initiatives. . He serves on the Cornell Swanson Engineering Simulation Industry Advisory Board, on the Board of Advisors for the University of Maryland Department of Aerospace, and is on the Board of Directors of the American Helicopter Museum and Education Center. Dan Chaired the NATO Industry Advisory Group (NIAG) Study Groups SG-219 Next Generation Rotorcraft Capabilities, SG-239 on Integrated Sustainability for the Next Generation Rotorcraft, and SG-266 on Joint-Domain NATO Rotorcraft Interoperability and Survivability in a Peer Nation Threat Environment. And he served on the 2020 National Academies Panel on Propulsion Sciences at the Army Research Laboratory (ARL), and 2018 National Academies Panel on Sciences for Maneuver at ARL. Dan received his Bachelor of Science in Mechanical Engineering from the Sibley School at Cornell University, and his Masters in Aerospace Engineering from the Alfred Gessow Rotorcraft Center at the University of Maryland where he was named a Distinguished Aerospace Engineering Alumnus. Dan has a recurring column in *Vertiflite* Magazine 'Coming to Terms'.